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In this issue

Response of Earth Dams to Earthquake Events – Field Data and Numerical Modelling

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Abstract

This paper is the written version of the SECED evening talk given at the ICE by the first author on 29 November 2017. It presents numerical analyses related to the seismic response of earth dams. A well-documented case study is considered, the La Villita earth dam in Mexico, for which relevant useful field data are available. The developed numerical model was able to simulate very well the recorded dam response under seismic loading and was used as a basis for a subsequent parametric investigation. Issues related to the stiffening effect of the narrow canyon, dam–reservoir interaction and dam–foundation interaction are discussed.

Introduction

Many earth dams around the world are located in zones characterised by moderate to high seismicity. Their seismic stability can be particularly critical for the safety of the areas in the downstream side and therefore an in-depth understanding of their response during earthquakes is required. Relevant experimental data are hard to obtain, as full-scale tests are very expensive to be performed and real data recorded from actual earthquakes are rare and sparse. On the other hand, sophisticated numerical models do exist nowadays, but they need to be calibrated against real measurements from previous earthquake events before they are used reliably for future design.

This paper presents the seismic response of the La Villita Dam in Mexico under two different earthquake events of distinct intensity. Analysis of the actual field data along with relevant static and dynamic nonlinear finite element (FE) analyses are presented and discussed to obtain an understanding of the behaviour of the dam. Such a validation is necessary to build confidence in the developed numerical models. Subsequently, several issues related to the general performance of dams during an earthquake are discussed, such as the stiffening effect of narrow canyon topography, dam–reservoir interaction (DRI) and the effect of the compliant dam foundation.

Case study: La Villita earth dam, Mexico

La Villita is a 60 m high zoned earth dam in Mexico, founded on a 70 m thick alluvium layer and built in 1967. The dam is composed of a central clay core, sand filters and rockfill shells. It has experienced a number of seismic events (among which the most significant was the M_s 8.1 Michoacán earthquake on 19 September 1985) sustaining some permanent deformations and crest settlements. Relevant details may be found by Elgamal (1992) and Pelecanos (2013).

Pelecanos et al. (2015) performed two-dimensional (2D) plane-strain static and dynamic coupled-consolidation FE analyses (cross-sectional geometry shown in Figure 1), employing the Imperial College Finite Element Program (ICFEP) (Potts and Zdravković, 1999; 2001; Kontoe, 2006). The full static stress history of the dam prior to the earthquake events (construction, reservoir impoundment and consolidation) was modelled prior to the dynamic analyses. The material constitutive model was a cyclic nonlinear elastic model which dictates the degradation of shear stiffness, G, and the increase of damping, ξ, with cyclic shear strain, γ, coupled with a Mohr–Coulomb yield criterion. The material properties were obtained from Elgamal (1992).

Figures 2a and 2b show a comparison of the response spectra derived from the numerical predictions of acceleration response at the crest of the dam during the 15/11/1975 and 19/9/1985 seismic events respectively, with those derived from the corresponding filtered recorded motions. The stiffening effect of the narrow canyon geometry was accommodated in a 2D plane-strain analysis by using an appropriate 'increased' value of the shear modulus, G, which was in accordance with the suggestions of Dakoulas and Gazetas (1987) for dams built in narrow canyons. Moreover, due to the possible existence of a localised slip failure close to the monitoring instrument at the crest (Elgamal, 1992; Pelecanos et al., 2015), the high frequencies of the recorded motion that corresponded to strike-slip failure were filtered. In general, Figure 2 shows that the developed numerical model was able to capture the response under both seismic events (of different magnitude, duration and frequency content) very well. It should be noted that the same set of soil properties and constitutive model parameters were used for both excitations.

Dam–reservoir interaction

In static conditions, the upstream reservoir induces hydrostatic pressures on the upstream face of an earth dam. Under seismic conditions, additional hydrodynamic pressures develop affecting the vibration of the dam which interacts with the vibration of the reservoir. The critical question is whether DRI effects are significant for concrete and earth dams.

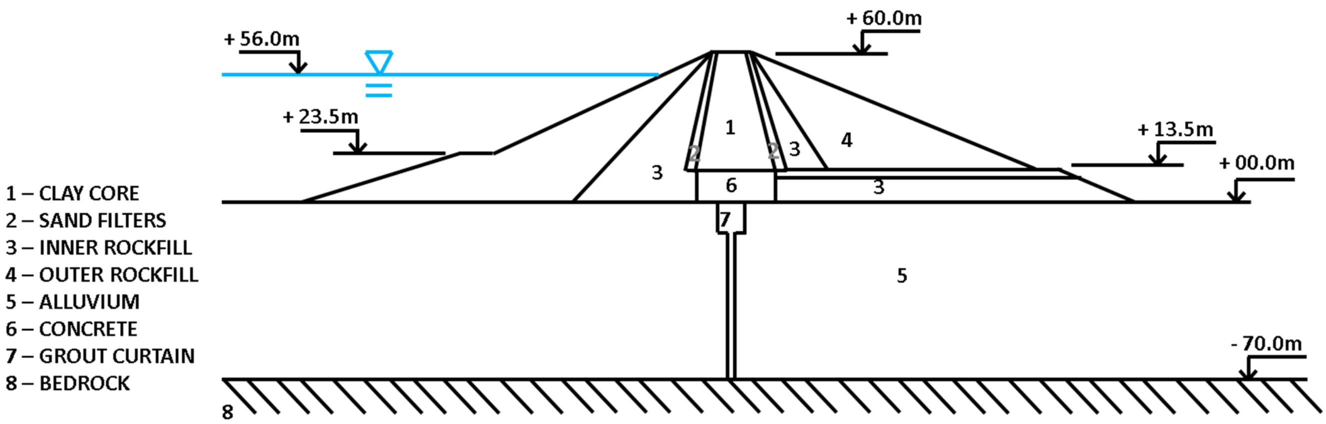

Figure 1: La Villita earth dam (Pelecanos, 2013).

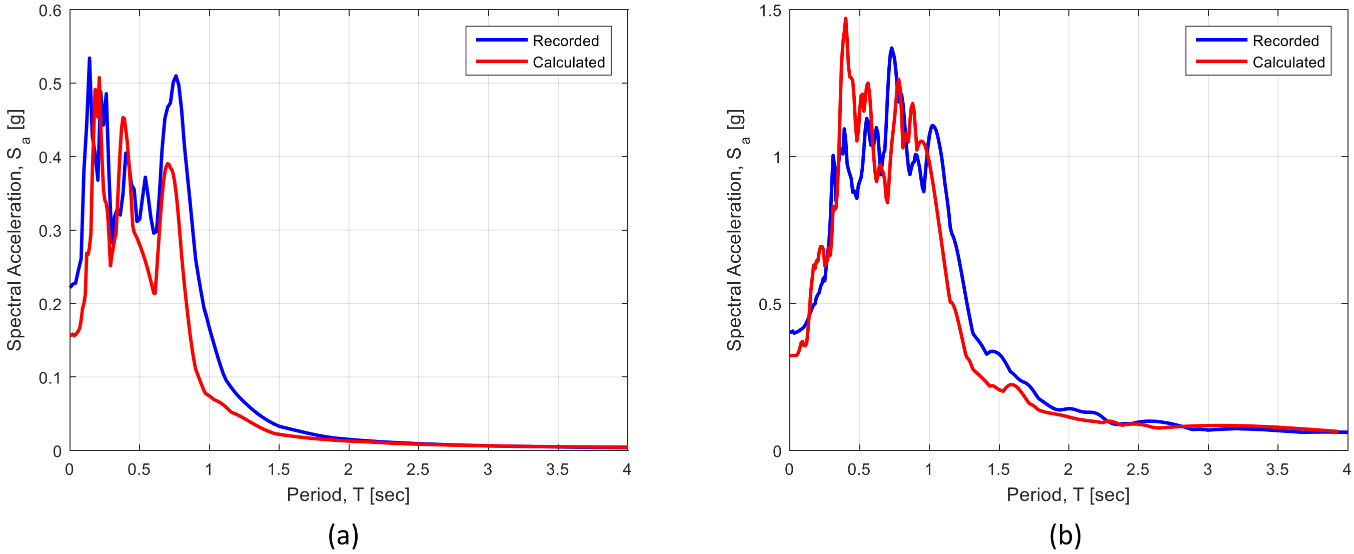

Figure 2: Seismic response of the dam – comparison of response spectra derived from recorded and calculated accelerations: (a) 15/11/1975 earthquake; (b) 19/9/1985 earthquake.

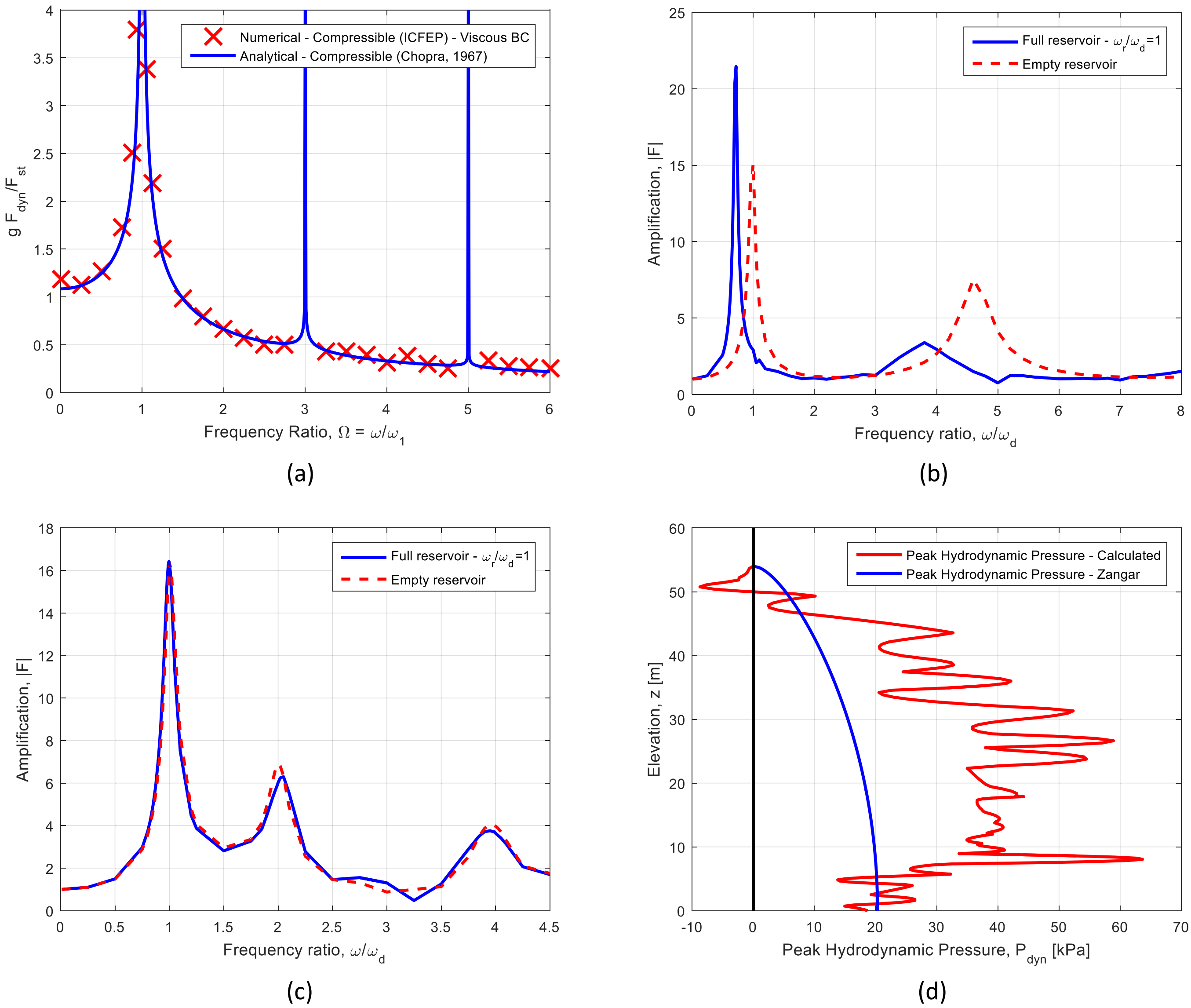

Figure 3: DRI: (a) Verification of numerical modelling (Pelecanos et al., 2013); (b) amplification of accelerations for concrete dams (Pelecanos et al., 2016), (c) amplification of accelerations for earth dams (Pelecanos et al., 2016); (d) transient hydrodynamic pressures (Pelecanos et al., 2018a).

Firstly, one needs to model in an appropriate way the hydrodynamic pressures by discretising the reservoir domain. A methodology was proposed by Pelecanos et al. (2013) in which the reservoir is modelled with elastic solid continuum elements having the bulk modulus of water (K_w = 2.2 GPa; i.e., compressible) and a small value of G. Interface elements can be placed between the reservoir and the dam/ foundation domains with high normal and small shear stiffness, while the Viscous or Cone boundary conditions (BCs) can be employed at the upstream truncated boundary. Extensive validation was carried out by Pelecanos et al. (2013) for various loading conditions and Figure 3a shows a comparison of the numerical predictions against the analytical closed-form solution of Chopra (1967) regarding the dynamic pressures spectrum. The latter figure plots the ratio of the total hydrodynamic force, F_{dyn}, multiplied by the acceleration of gravity, g, over the hydrostatic force, F_{st}, on the upstream face of a model dam, against various values of the ratio, Ω, of the circular frequency of the excitation, ω, over the fundamental circular frequency of the reservoir, ω_1.

Pelecanos et al. (2016) studied the visco-elastic dynamic DRI response of model concrete and earth dams and found that DRI affects both (i) the amplification of accelerations and (ii) the natural frequency of vibration of dams. The effects are more pronounced for concrete dams, as shown in Figures 3b and 3c. The latter figures plot the amplification of accelerations, $|F|$, at the dam crest with respect to the ratio of ω over the fundamental circular frequency of the dam, ω_d.

Nonlinear transient dynamic FE analysis of La Villita Dam was performed by Pelecanos et al. (2018a) with a discretised reservoir calculating the reservoir hydrodynamic pressures. Figure 3d plots the calculated profile of maximum hydrodynamic pressures, P_{dyn}, on the upstream face of the dam during the 19/9/1985 Mexico earthquake, and compares that to the analytical solution of Zangar (1952). The latter solution underestimates significantly the hydrodynamic pressures due to the adopted assumptions of incompressible reservoir and rigid dam.

Dam–foundation interaction

Pelecanos et al. (2018b) examined the seismic response of La Villita Dam (which is built on a compliant foundation layer) as if it was built on a rigid foundation. Two approaches were followed; (i) using the bedrock motion directly as an input, and (ii), performing first a site response analysis of the foundation layer to obtain the ground surface response and using this as an input to the analysis of the dam built on a rigid foundation.

Figure 4 plots the response spectra of the calculated accelerations at the dam crest, and compares them to the response spectrum corresponding to the case of the full dam–foundation system. The two attempts to decouple the dam–foundation interaction predicted significantly higher values of spectral accelerations, which is rather conservative, and therefore the above approaches are not recommended for use in practice. Instead, it is suggested that dam–foundation systems are modelled in a monolithic way as in Pelecanos et al. (2015).

Conclusions

This paper presents a series of nonlinear FE analyses related to the seismic response of earth dams. A well-documented earth dam, the La Villita earth dam in Mexico, for which available useful field data are available, was used as a case study. The findings of this study may be summarised as follows:

- Earth dams can be significantly affected by earthquakes and may sustain considerable settlements, deformations and slope instability.
- Dams built in narrow canyons exhibit a stiffer response than dams built in wide canyons, and therefore a full three-dimensional numerical analysis is required in the former case. However, a 2D plane-strain analysis with an increased value of material stiffness is

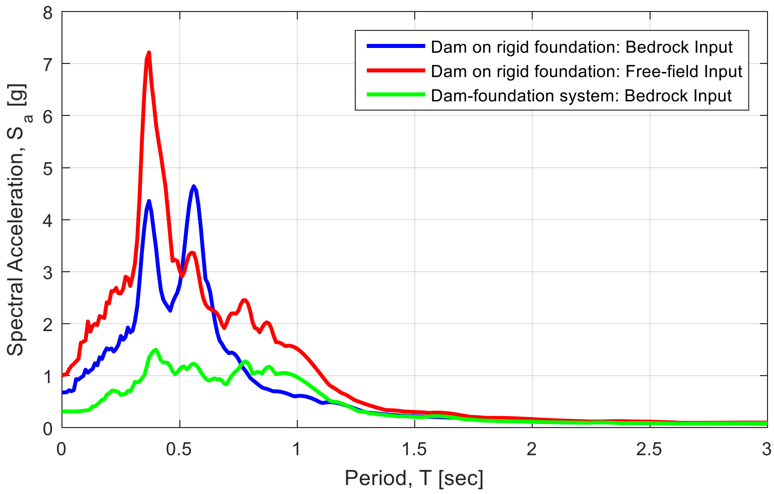

Figure 4. Response spectra at the crest of the dam for different modelling approaches of dam–foundation interaction (Pelecanos et al., 2018b).

computationally more efficient and a reasonable compromise.

- The reservoir domain may be modelled with elastic solid compressible finite elements. The Viscous or Cone BCs may be used at the upstream truncated boundary.
- Dam–reservoir interaction affects both the amplification and the frequency content of dam accelerations. It is found to have a larger effect on concrete dams than earth dams. The analytical relation of Zangar (1952) appears to under-predict the hydrodynamic pressures.
- Dam–foundation interaction affects the seismic response of earth dams. The foundation soil should not be ignored in an analysis; instead a dam–foundation system should be modelled in a monolithic way.

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